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The effect of a heat treatment on improving the fatigue properties of aluminium alloy 7075-T6 coated with TiN by PVD

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Abstract

In this paper, fatigue properties of coated aluminium alloy 7075-T6 with a TiN deposit of 3 µm using physical vapour deposition (PVD) have been studied. It was determined that the application of a PVD hot process significantly decreased the tensile and fatigue strength of the substrate-coating system due to the effect of a high operating temperature (450° C). Fatigue life of the coated aluminium showed a considerable reduction of 94% in the fatigue life after experiencing the deposition temperature. Taking into consideration the effect of the high deposition temperature to remove the benefits of T6 from the aluminium alloy, it was therefore believed that re-applying the T6 cycle could recover the lost properties of the aluminium substrate. The tensile and fatigue tests results after applying the post heat treatment revealed large improvements in the yield, ultimate and fatigue strength of the coated material to approach initial properties of the uncoated 7075-T6.

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Keywords: Low and high cycle fatigue; 7xxx Aluminium alloys; PVD hard coatings; heat treatment.

1. Introduction

Single metal nitrides such as TiN, CrN and ZrN are classified as hard physical vapour deposition (PVD) coatings which have been commercially used in cutting applications because of their high hardness. However, these PVD coatings are also extensively used in wear and corrosion protection applications and they are now widespread in global manufacturing for reducing production costs and

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improving productivity, all of which is essential if industry is to remain economically competitive [1]. Titanium nitride (TiN) is the most common PVD hard coating which is well-known as a wear resistance coating material with a low friction coefficient that can eliminate fretting and adhesive wear, and provide smooth operation between moving components such as mechanically fastened joints under fatigue loading conditions. It may be therefore considered as a good coating material to improve wear and fretting wear as well as corrosion behaviour of aerospace structural components made from high strength aluminium alloys. However, generally, the PVD processes used to deposit such coatings require depositional temperatures of 400-500° C that may considerably affect mechanical properties of the coating-substrate system.

A survey of the literature confirmed that mechanical properties of structural coatings have been the subject of intensive research. There are many studies conducted on properties such as corrosion, hardness, tribological, and thermal conductivity for a wide variety of coatings [2-7]. However, fatigue failure analysis of coated materials is much more complicated than that of the uncoated, as failure occurs in an adhesively bonded bi-material system, including a thin layer of the coating material and a substrate. The fatigue response of a SAE 4340 steel substrate coated with TiCN (4 μm in thickness) by plasma assisted physical vapour deposition (PAPVD) was studied in air and in a 3 wt.% NaCl solution [8]. The results showed a considerable increase of 140%-180% in the fatigue life of the coated steel tested in air and a marginal increase of 25% in the corrosive environment. This revealed that the TiCN coating was susceptible to the corrosive solution under fatigue loading conditions.

It was reported that coating aluminium alloy 7075-T6 with an electroless nickel-phosphorous (Ni-18P) film of 38–40 μm in thickness improved the fatigue and corrosion fatigue behaviour of the aluminium substrate [9]. However, PVD-ZrN coatings of 3 μm in thickness significantly reduced both the tensile and fatigue properties of the aluminium alloy (7075-T6) substrate [10]. 43% and 28% reductions in the yield and tensile strength of the aluminium substrate were noted, respectively. This was in association with a 73%–82% decrease in fatigue life during air testing and 11%-51% in the 3 wt.% NaCl solution. It was therefore concluded that the ZrN coating could partially compensate for the decrease in the fatigue strength of the coating-substrate system in corrosive conditions. The high operating temperature of the PVD process was believed to decrease the yield, tensile and fatigue properties of the coated material.

Considering detrimental effect of the PVD high operating temperature on the tensile and fatigue properties of alloy 7075-T6, this work is to study the effect of a post heat treatment on improving the fatigue properties of Al 7075-T6 coated with TiN by a PVD process. To accomplish this, fatigue strength of uncoated substrate, coated material and coated material subjected to the applied heat treatment were evaluated.

2. Details of experimental work

According to the ASTM E466 standard, flat fatigue test specimens were manufactured from an aluminium alloy 7075-T6 plate (bare condition) with a thickness of 3.175 mm, as shown in Fig. 1. The longitudinal axis of all the specimens was aligned with the rolling direction of the plate. The specimens were initially polished with silicon carbide papers of 600, 800 and 1200 grits and then subsequently polished with a sisal mop (white BBB U-lime) and a cotton mop (BBB green rouge) to achieve a mirror-like finish without leaving any small scratches on the surface. A number of tensile test specimens were also made from the aluminium plate according to the ASTM E8 standard.

The aluminium substrate specimens were coated with 3-μm-thick titanium nitride (TiN) coatings using a Physical Vapour Deposition (PVD) process with a high-purity titanium target (99.999 at.%) by Guhring Australia Pty. Ltd. Before mounting the substrates onto the fixtures of the PVD vacuum chamber, the specimens were cleaned in order to remove dust, oils and fingerprints to produce a clean surface. The specimens were then loaded into the chamber and subjected to an argon ion plasma etching process to remove any oxide film prior to the coating deposition. The maximum operating temperature of 450° C was applied to the aluminium specimens during the pre-heating, argon etching and coating stages for two hours. The coating thickness was determined by the CSEM ball cratering technique to be 3 μm.

Prior to design of fatigue tests, tensile properties of coated specimens as well as uncoated specimens were evaluated. The yield strength of Al 7075-T6 largely decreased from 520 MPa to 110 MPa (78%) when coated with TiN. Similarly, a considerable reduction of 54% was observed in the ultimate strength (from 580 MPa to 263 MPa). Such a significant decrease in the tensile properties ensured a considerable reduction in the fatigue strength of the coated material. It was therefore believed that performing an appropriate post heat treatment could restore the lost tensile properties caused by the PVD hot process.

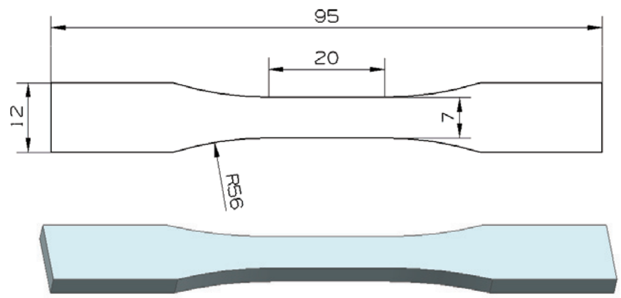


Fig. 1. Fatigue test specimen, dimensions are in mm.

The high operating temperature of the PVD process (450° C) applied to the Al 7075-T6 substrate for 2 hrs was believed to soften the material and diminish the advantages of the T6 temper process. Therefore, repeating the solution heat treatment followed by artificial aging (T6) after the deposition process was considered as the PHT for the coated specimens. To do that, the specimens were heated up to 485° C rapidly and held at 485° C for 1 hr followed by two-stage quenching; initially hot quenched into 60° C water for 6 seconds and then promptly transferred to a cold water quench bath (25° C). Then, the quenched specimens were heated up again to 121° C and held at 121° C for 24 hrs followed by cooling in the air to room temperature. The post heat treatment could successfully restore most of the lost tensile properties of the coated specimens. Large improvements of 243% and 77% were observed in the yield and ultimate strength of coated specimens respectively as a result of the applied PHT.

A MTS fatigue testing machine (model 858) was used to conduct the fatigue tests with constant-amplitude at a load frequency of 15 Hz (sinusoidal loading) with a load ratio of R=0.1. Three batches of Al 7075-T6, Al 7075-T6 coated with TiN and Al 7075-T6 coated with TiN+PHT were fatigue tested. For each batch of specimens, four tests were performed at four different levels of cyclic loading. At each level, a minimum of three fatigue tests was carried out. The average values of the obtained fatigue lives were then determined in order to obtain the S-N curve of best fit for each batch. The number of cycles to completely fracture the specimen was recorded as the fatigue life of the specimens.

3. Results

Fatigue life results were plotted in a semi-log S-N diagram, as shown in Fig. 2. It can be clearly seen that the coated specimens experienced significantly less number of fatigue cycles compared to Al 7075-T6. Approximately, a 94% reduction in the fatigue life was found when the coated material was tested at a maximum alternating stress of S_{max}=244 MPa. Such a considerable decrease was therefore attributed to improve the fatigue life of the coated specimens substantially. A 468% improvement in the fatigue life was observed at S_{max}=244 MPa, although the PHT could not fully regain the lost fatigue properties to achieve those of the original Al 7075-T6.

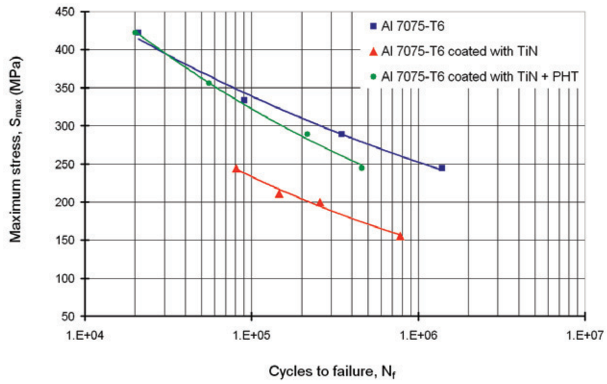
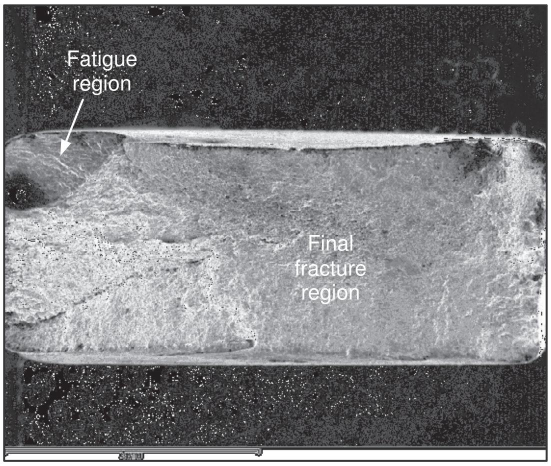


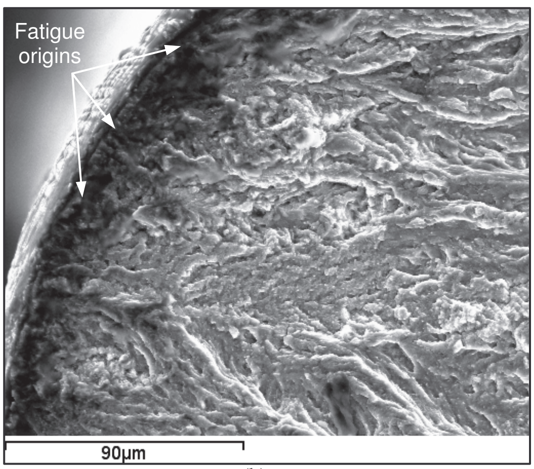
Fig. 2. Stress versus life (S-N) curves for tested batches at R=0.1.

4. Fractographic analysis

Fatigue fracture surfaces of selected coated and coated+PHT specimens were examined at high magnifications using scanning electron microscopy (SEM) to identify fatigue crack initiation locations and to determine the occurrence of delamination of the coating from the substrate. The fracture surfaces of two specimens from the coated and coated+PHT batches are shown in Figs. 3 and 4, respectively. A general view of the fracture surface is firstly shown which comprises of fatigue and final fracture regions. Moreover, a further magnification better highlights the crack nucleation site at which possible fatigue crack origins are indicated. Macro- and micro-fractographic features of the coated+PHT specimens were similar to those of the coated specimens. Also, as can be seen in both Fig. 3b and 4b, fatigue cracks initiated from the corner of the fracture surface at or near the outer surfaces of the aluminium substrate. Generally, fractography of the coated and coated+PHT specimens at high magnifications did not reveal any significant delamination of the TiN coating layer from the aluminium substrate under the applied cyclic loading with low and moderate maximum stresses. However, substantial delaminations were locally observed in the coated and coated+PHT specimens that failed under high alternating loads. For example, Figure 5 displays the delaminated regions with further magnifications of the coated+PHT specimen which failed at the highest maximum alternating stress.

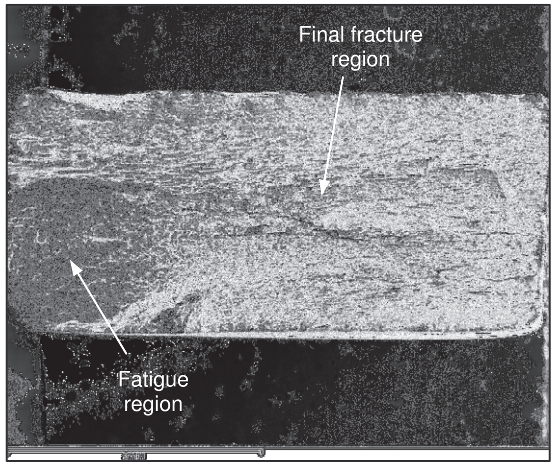


(a)

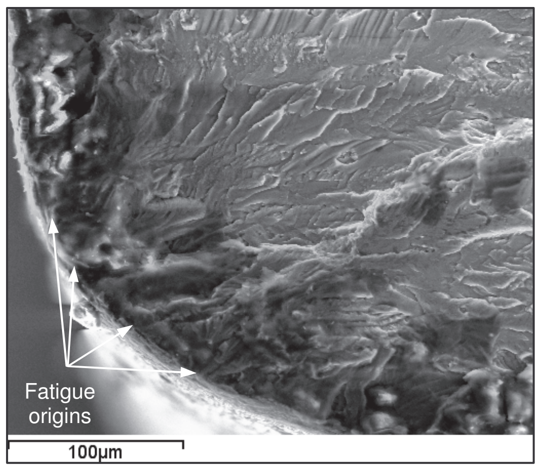


(b)

Fig. 3. Al 7075-T6 coated with TiN specimen failed at S_{max}=244 MPa: (a) Fatigue fracture surface; (b) Detailed view of the fatigue crack nucleation site.



(a)



(b)

Fig. 4. Al 7075-T6 coated with TiN+PHT specimen failed at S_{max}=422 MPa: (a) Fatigue fracture surface; (b) Detailed view of the fatigue crack nucleation site.

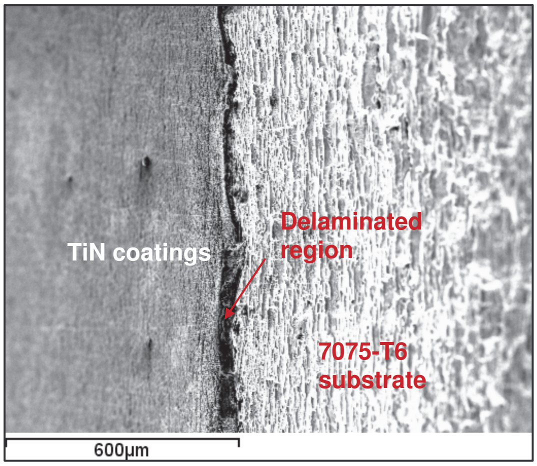


Fig. 5. Delamination of TiN coating layer from aluminium substrate; coated+PHT specimen failed at high maximum stress of 422 MPa.

5. Discussion

It is noted that the high operating temperature of the PVD process (450° C applied for 2 hrs) could remove the expected benefits of T6 from the previously heat treated aluminium alloy (Al 7075-T6). The large reduction in the tensile properties of the alloy exposed to the deposition heat was believed to be due to the growth of the strengthening precipitates as a consequence of overaging the previously T6-treated alloy. Consequently, a significant reduction was observed in the fatigue strength of the coated specimens. The low tensile strength of the coated Al 7075-T6 reduced the endurance limit of the coating-substrate system considerably. However, re-applying the T6 cycle re-dissolved the grown precipitates and produced a solute rich solid solution again. Therefore, the tensile properties and fatigue strength of the coating-substrate system were considerably increased.

6. Conclusions

- Aluminium alloy 7075-T6 substrate coated with 3 μm thick TiN by PVD showed large reductions of 78% and 54% in the yield and tensile strength respectively. Also, a significant decrease of 94% in fatigue life of the coating-substrate system was noted comparing with the original Al 7075-T6. The high operating temperature during the deposition process was responsible for the decrease in the tensile and fatigue properties of the coated Al 7075-T6.

- The applied post heat treatment satisfactorily restored most of the lost tensile and fatigue properties, although they were not fully recovered. The fatigue life of the coating-substrate system was substantially prolonged by approximately 450% after application of the post heat treatment.

- Under low and moderate alternating loads, the thin TiN film was well-adhered to the aluminium substrate and no delamination was observed. However, significant delaminations occurred under high fatigue loads.

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